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ROBOTIC HIGH PRESSURE WATER JET CUTTING OF CHUCK SLICES[1]

ABSTRACT

With the objective of producing high quality and economical starting material for restructured beef products, the use of a high pressure water jet was investigated for excising objectionable material from slices of bone-in beef chuck. From the limited number of tests conducted, best conditions for a clean, smooth cut were obtained with a water jet orifice diameter of 0.15 mm (0.006 in), a water pressure of 380 MPa (55,000 PSI), a slice thickness of 19 mm (3/4 in) and a linear cutting speed of 10.9 m/min (430 in/min). A preliminary cost comparison indicated that a fully automated line had a greate economic advantage over the manual method.

INTRODUCTION

Water erosion is a well known natural phenomenon, responsible for the smoothing of old mountain ranges, or the gouging of valleys as awesome as Arizona's Grand Canyon. Using the water jet, man has harnessed this phenomenon to cut materials as soft and flimsy as disposable baby diapers or as hard as rock, even man-made ceramics. The water jet may be used in combination with mechanical cutters or the jet may be pulsed. Both are effective assists in fracturing brittle materials and are applied in mining and oil well drilling (Saunders 1977; Lee 1975; Maurer 1975). The addition of long chain polymers to the water reduces the diversion of the jet stream (Franz 1972), while the addition of abrasives by means of a secondary jet allows for the cutting of very hard and tough materials, like ceramics (Smoluk 1986). The dustless action of the water jet makes it environmentally safe for cutting asbestos sheets and brake linings (Martin 1980).

Commercial applications of water jet technology in the food area are few. Brierly (1975) reported the halving of freestone peaches and Shield *et al.* (1973) investigated high speed cutting of lettuce stems. The water jet is ideally suited for robotic positioning due to its omnidirectional feature and instantaneous on/off capability. An automatic and continuous process envisioned for the preparation of restructuring material (Heiland *et al.* 1987) would utilize high pressure water jets for a sanitary, high speed excision of objectionable material (bone, fat, gristle) from slices of beef chuck. The two key elements of this automatic process are the detection by an optical sensor (Konstance *et al.* 1988) and the excision of objectionable materials. The objective of this study was to demonstrate the potential of water jets for this excision operation.

MATERIALS AND METHODS

USDA choice grade, square-cut chucks (#113, NAMP, 1984), Yield Grade 2 steers were used in this study. The chucks were frozen at −20 °C, then tempered at −5 °C for two days and sliced on a band saw. The saw (Biro Manufacturing Co., Marblehead, OH, Model #33) had a custom made saw table extension to accomodate chucks weighing up to 53 kg and a base extension to prevent the saw from tipping. The chucks were sliced, starting from the fifth rib, to different thicknesses of 12.5, 25, 50 and 100 mm. These slices were vacuum packaged (Smith Equipment Co., Clifton, NJ, Supervac Model GK 120) and returned to −20 °C storage.

A Water Jet Knife, (Flow Systems, Inc., Kent, WA) that consisted of small sapphire nozzles and a model 11XD-MK2-55 internsifier pump capable of delivering 4.69 L/min (1.24 Gpm) at 380 MPa (55,000 PSI) was used. At this pressure, water is 12% compressed (Martin 1980) and the water jet operates with a stream velocity of Mach 3 (Buck *et al.* 1979). Remote manipulation of the nozzles was accomplished with a 59 kg (130 lb) industrial programmable robot (ASEA Robotics, Inc., New Berlin, WI). This combined system was located in the Mechanical Engineering Department, College of Engineering, University of Rhode Island. Experiments were conducted at URI to determine the maximum linear traverse speed for each condition that cut completely through red meat, fat and connective tissue. The following variables were studied: (1) meat temperature (frozen versus unfrozen), (2) slice thickness, (3) intensifier pump pressure, (4) nozzle orifice diameter of the water jet and (5) speed limitations imposed by the robot's inertia when programmed to follow intricate patterns, e.g., those required for the excision of bone.

Residual bone matter was determined by measuring calcium concentration using atomic absorption (AOAC 1984).

TABLE 1.
MAXIMUM LINEAR TRAVERSE SPEEDS OF WATER JET THAT RESULTED IN COMPLETE SEVERING OF RED MEAT, FAT AND CONNECTIVE TISSUE IN UNFROZEN (+3 °C) SLICES OF BEEF CHUCK - WATER JET OPERATED WITH 380 MPa PRESSURE AND A 0.15 mm NOZZLE ORIFICE DIAMETER

Slice Thickness (mm)	Linear Traverse Speed (m/min)	Kerf Loss[1]		Remarks
12.5	25	very little	(< 2%)	clean cut through full thickness
25	5	very little	(< 2%)	clean cut through full thickness
50	1	great	(> 5%)	lower half of cut very rough and wide
100	0.2	excessive	(> 10%)	lower half of cut extremely ragged and very wide

[1]Based on an average length of excision cut of 2.5 m/slice and an average slice area of 0.1 m^2.

RESULTS AND DISCUSSION

The linear traverse speeds that resulted in complete cuts through beef chuck slices of varying thickness are shown in Table 1. Red meat, fat and connective tissue were completely severed while bone was only slightly scored. All data in Table 1 were obtained with the intensifier pump operating at 380 MPa and a 0.15 mm nozzle orifice diameter. Based on a number of preselected linear traverse speeds Table 1 indicates that the linear traverse speeds V are inversely proportional to the 2.32 power of the slice thickness t:

$$\frac{V_1}{V_2} = \left(\frac{t_2}{t_1}\right)^{2.32} \tag{1}$$

For a water pressure of 380 MPa and a 0.2 mm orifice the exponent of this relationship was found to be 1.82. Because of the preselected linear traverse speeds and the somewhat subjective observation of the quality of the cut the linear traverse speeds are assumed to be inversely proportional to the square of the slice thickness, and Eq. (1) becomes;

$$\frac{V_1}{V_2} = \left(\frac{t_2}{t_1}\right)^{2} \tag{2}$$

While larger orifice diameters allowed faster traverse speeds (e.g., by using a 0.2 mm orifice, a 25 mm thick slice could be cut at 7.5 m/min and a 100 mm slice could be cut at 0.6 m/min with a 0.25 mm orifice), more water was required which reduced the number of water jets that can be operated from one intensifier pump (the intensifier pump used had the capacity to simultaneously operate six nozzels with a 0.15 mm diameter or one nozzel which a 0.33 mm diameter orifice). Without additives and at pressures up to 380 MPa, slices 50 mm thick or thicker could not be cut cleanly, regardless of orifice diameter. Also, kerf losses increased with orifice diameter.

An attempt was made to establish conditions under which the water jet would deflect when impacting bone. It was the objective to produce an excision that followed the surface contour of a bone, especially when not perpendicular to the slice surface. Impingement of the jet on bone resulted in reflection in all cases at any angle of impingement, even at lower intensifier pump pressures (e.g., 275 MPa). The impingements caused a slight scoring of the bone surface; score depth was visually judged to be inversely proportional to the linear traverse speed of the water knife. This erosive action removed a small amount of bone in powdered form but never generated any bone chips, a very desirable, inherent feature of water jet excision.

Cutting of slices of frozen (−5 °C) beef chuck could be done at linear traverse speeds equal to those of unfrozen (+3 °C) slices of equal thickness. After cutting, refreezing along the cut lines did not occur.

Meat samples, immediately adjacent to bone, that were subjected to water jet impingement, were analyzed to determine evidence of residual, powdered bone matter (mg/g calcium). The results, shown in Table 2, indicate that the calcium concentration of these samples, including the control samples from the same slices, is well within the range of naturally occurring calcium (0.09 - 0.13 mg/g)(Watt *et al.* 1963). Bone powder, that may be created, is evidently washed away by the very stream that produces it.

Removal of objectionable tissue and bone required that the water jet was guided through intricate paths and patterns. Inertia limitations of the robot arm that controlled the water jet lowered the high linear speeds otherwise possible with 12.5 mm thick slices. At a linear speed of 10.9 m/min, precise control of the robotic arm through intricate paths was "state of the art" and Eq. (2) yielded a corresponding slice thickness of 19 mm. At this slice thickness, anatomical changes between slices are manageable during the automatic excision of objectionable material.

This study demonstrated the applicability of robotic water jet excision of objectionable material from slices of beef chuck. Data from this study were used in a cost study comparing manual versus automated preparation of starting material for restructured beef products. This cost study showed that the automated system with an annual production rate of 7.6 million kg (16.8 million lb) would save at

TABLE 2.
CALCIUM CONCENTRATION IN MEAT SAMPLES
CUT BY WATER JET ADJACENT TO BONE

Sample #	Sample Weight (g)	Calcium Concentration (mg/g)
1	7.16	0.139
2	3.86	0.109
3	2.18	0.138
4	2.59	0.100
5	4.05	0.084
Control	4.29[1]	0.160[2]

[1]Average sample weight over 6 samples.
[2]Average calcium concentration of control samples.

least \$0.5 million over a manual method employing 20 meat cutters each in two shifts. Utilizing a slice thickness of 19 mm and a 0.15 mm nozzle orifice diameter, the automated system made optimum use of the intensifier pump's capacity. At the same time the linear traverse speed did not exceed the inertia limitations of the robot, the number of slices per chuck was manageable and the anatomical changes between subsequent chuck slices was minimal.

ACKNOWLEDGMENTS

The authors wish to acknowledge Dr. Thomas Kim, Chairman, Mechanical Engineering Department, URI, Dr. Hermann Viets, Dean, College of Engineering, URI and Mr. Thomas Stefanik, Regional Sales Manager, Flow Systems, Inc. for their cooperation and Mr. David Hunt, Water Jet Knife Operator and Graduate Student, URI and Mr. Ralph Bruch, USDA for their invaluable assistance with this work.

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